FIBER OPTICS HANDBOOK

SERIES 50-2

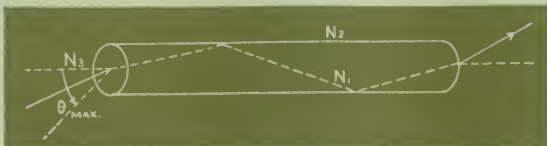
MOSAIC FABRICATIONS, INC.
STURBRIDGE, MASS

OPTICAL CONSIDERATIONS

Fiber optics transmission is basically a wave guide phenomenon, but geometric optics (ray tracing) will suffice for us.

NUMERICAL APERTURE

Light striking a fiber end within a certain maximum cone angle will be totally reflected from the sides and conducted as shown:



From Snell's law one sees that the maximum angle which gives conduction is

$$n_3 \sin \theta \max = \sqrt{n_1^2 - n_2^2}\,[1].$$

[1] This is exact only for meridional rays (those that intersect the axis). Skew rays outside this angle can be conducted by circular, and to some extent, eliptic fibers.

By analogy with lens optics we define $n_3 \sin \theta \max$ = numerical aperture (or n.a.). This quantity is a measure of light gathering power.

SOURCE DISTRIBUTIONS

A Lambertian source plane (one which looks equally bright from all directions) emits a flux proportional to the cosine of the angle from the normal. Mat white paper and phosphors are approximate examples. In the Lambertian case the flux contained out to an angle θ is proportional to $\sin^2\theta$.

Thus the square of the numerical aperture is the measure of light gathering power.[2]

CONSERVATION OF θ

Going back to the ray discussion, it is important to remember that (1) ideally the ray

[2] For those used to photographic terminology, f/number $= \dfrac{1}{2 \text{ n.a.}}$. A low f/number indicates large light gathering power. It will be apparent that in air where n_3 is unity the n.a. can't exceed unity and the f/number can't be less than ½.

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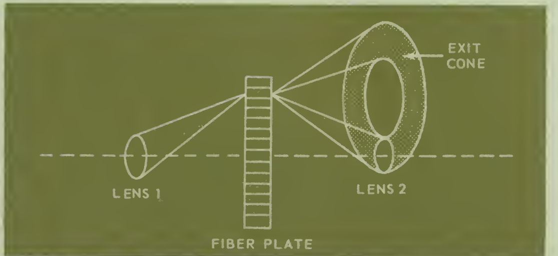
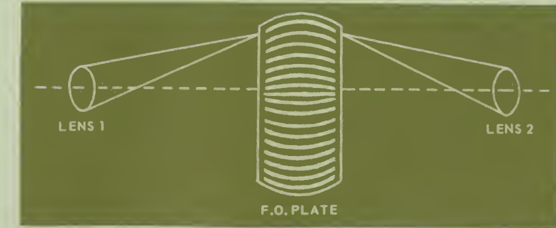
will emerge at angle θ, and (2) the azimuthal angle on leaving varies so rapidly with θ, length, diameter, etc., that practically it will spread to fill an annulus of a cone of half angle θ.

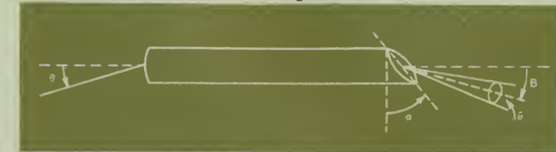
Consider this system



Only a small fraction of the light will strike the second lens. Clearly, it is important to remember this effect. A modification of this system is said to have "field angle correction."



Another point to remember: a biased end cut acts as a prism and the exit annulus will be tipped towards the apex.[3]



Preservation of angle θ on leaving is only an approximation. Diffraction at the ends,

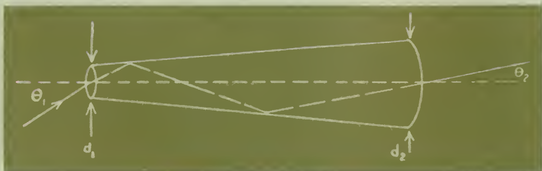
[3] $\beta = \sin^{-1}\left(\frac{n_1}{n_3}\sin a\right) - a$ or $\sim\left(\frac{n_1}{n_3} - 1\right)$ for small angles.

bending, striae, and surface roughness will decollimate (open up the annulus).[4]

One should remember this limitation is operating into slow optical systems.

TAPERED FIBERS

Regarding tapered fibers there is one important law:



$$d_1 \sin \theta_1 = d_2 \sin \theta_2.$$

[4] Only roughness causes progressive decollimation; the others may be regarded as junction effects.

The effect of this is that light entering the small end becomes more collimated as the diameter increases. Light entering the large end becomes decollimated and if the angle exceeds the acceptance angle it will spill out the side.[5]

Probably the most frequent error made by the novice is the attempt to condense an area of light which is already Lambertian. This only throws light out the sides. If the in-

[5] Conversely light approaching the side as shown will be trapped. This forms the basis for one kind of injection lighting. In some

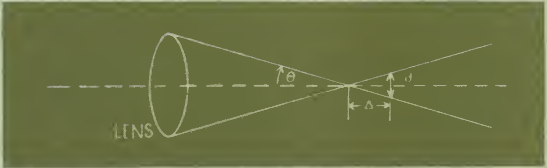
cases the side should be blackened to avoid stray light, although such light will ideally lie outside the image cone.

coming light is in a small angle, then the outgoing flux per unit area can be increased.

In working with a "Mae West" system, remember that it is the smallest diameter which determines the acceptance angle of the system.

DEPTH OF FOCUS

The depth of focus of a fiber system, as for a lens system, depends on the f/number or n.a.



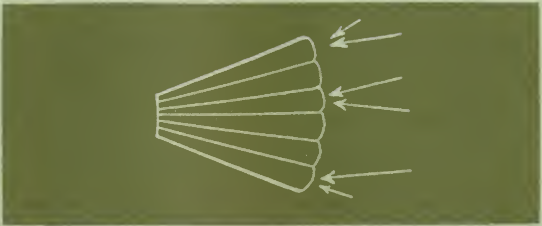
$$\frac{d}{2\Delta} = \tan\theta \sim \sin\theta \text{ for small angles.}$$

d = desired resolution diameter.
Δ = depth of focus.

Image Formation

Fiber optics can never "form" an image or transport an "unformed" image. The end surfaces of the fiber optics should in all cases be image surfaces.[6]

One exception of interest is the house fly. Its eye is an array of tapered fibers which form a narrow acceptance angle for each



fiber. Each fiber looks in a different direction.[7]

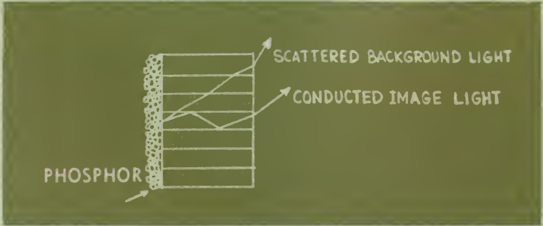
[6] The ability of a lens to form an image depends on making a phase transformation on a wave front. Although fibers carry phase information, because the multiplicity of wave guide modes and, hence, propagation constant, each fiber acts as a diffraction grating. Moreover, minute diameter variations from fiber to fiber produce enormous phase changes.

[7] It was once supposed that each facet of the eye formed a separate image. It is improbable that nature would go so far to confuse a fly; she reserves her talents for mankind.

ARRAYS OF FIBERS AND CLADDING

The discussion so far has concerned single fibers. When fibers are bunched together in an orderly array, according to electromagnetic theory, light will jump from one fiber to another close by (in analogy to the tunnel effect of quantum mechanics). For this reason, among others, optical fibers are usually made with a low index cladding of sufficient thickness to insulate the light-conducting channel from the outside world. This cladding is most frequently glass, and in fused arrays the cladding bonds the fibers to form a solid material.

In optical mosaics (fused assemblies) it is common to apply a second cladding of opaque material around each fiber to absorb light outside the acceptance angle. In the illustration at the left, phosphor emits light in all directions. Light inside the acceptance angle will form an image. Light outside will be scattered. When viewing by eye within the acceptance angle this scattered light won't be observed. When printing directly on film it will degrade contrast. An optical mosaic with this second opaque cladding is said to have extramural absorption or ema.



RESOLUTION

When a fiber optics device is moved relative to the object, the resolving power is well defined and is that of a flying spot scanner of spot size equal to the fiber core size. As a rule, one can resolve 0.8 line pairs per fiber diameter, starting with a high contrast target.

With a fiber optics device not in motion, the resolution is not well defined. Again, as a rule of thumb one can resolve about 0.5 line pairs per fiber diameter. However, the pic-

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ture quality is poor and it is well to be conservative in estimating resolving power.[8] One can assume that the resolving power in lines per unit length is

$$\frac{1}{R^2}_{\text{System}} = \frac{1}{R_1^2} + \frac{1}{R_2^2} + \frac{1}{R_3^2} + \ldots\ldots,$$

Where R = Resolution of any system element or that the effective fiber diameter of the system is

$$D^2_{\text{System}} = d_1^2 + d_2^2 + d_3^2 + \ldots\ldots$$

Where d = fiber diameter of an individual plate. Actually, the picture appearance of a static system of four cascaded 10-micron mosaics is better than that of a 20-micron single mosaic.

[8] In terms of information theory, the static resolving power for line pairs is actually higher than the dynamic resolving power. Nevertheless, in terms of quick recognition it is empirically as stated. The apparent resolving power of static systems for random small figures (as opposed to long edges) is about 1/3 as good as in a dynamic system for shape recognition, but 2/3 as good in counting the number of figures. For best visual results, one should present a static mosaic to the eye with just enough magnification to resolve the fiber structure. More magnification makes the fiber structure distracting and hampers the recognition process.

TYPES OF FIBER OPTICS AND THEIR PERFORMANCE CHARACTERISTICS

Fiber optics components come in several forms. Many of the comments which follow are related to the present state of the art and are not immutable truths.

SINGLE FIBERS

These can be supplied in sizes from 2 microns up to ¼ in. (and possibly larger and smaller), and in lengths up to 150 ft. It is extremely difficult to handle a fiber less than 50 microns (0.002 in.), and smaller sizes are not recommended for general use. For scientific purposes, a core of very small diameter can be supplied in a cladding of very great diameter to permit easy handling.

Single fibers commonly have numerical apertures from 0.2 to 1.0. The n.a. obtained by using unclad fibers or by depending on the external glass-air interface can be 1.4 without difficulty. However, we do not recommend this use. Only the most careful mounting and scrupulously clean handling will give

good results with unclad fibers.

For most glasses, spectral transmission will fall off beyond 4000 Å in the blue and 1.5 microns in the red in long lengths. Some manufacturers supply arsenic trisulfide for use in the infrared; others are working on silver chloride. Quartz can also be obtained, but as yet without protective cladding.[9] Plastic fibers with plastic cladding are available.

Maximum operating temperature depends on mechanical damage and transmission. Fibers can be made to stand intermittent temperatures of 1200°F[10] or greater, but most become quite absorbent above 800°F so that it is not always possible to see through them even if they are not permanently damaged on return to a lower temperature. As a rule of thumb, the safe short-time bending radius is $R = 50d + 1000d^2$ where R is the bending radius in inches and d is the fiber diameter in inches. This relationship is approximately true for fiber diameters from 0.002 in. to 0.04 in. The long-term safe bending radius is at least ten times this amount and depends on tempering in the drawing process.

Fibers with prestressed cladding can be supplied. These have a long-term safe bending radius about one-and-one half times as great as that given in the formula. In any case, fiber breakage is statistical.[11]

LIGHT CONDUIT

This next more complex device is composed of an aligned flexible bundle of singles.

FLEXIBLE FIBERSCOPES

These are aligned bundles of fibers. The safe bending radius of a flexible bundle depends mostly on construction, packaging, and surface treatment, and can't be deduced from fiber size. This bundle is a flexible image-carrying device.

[9] Liquid, and crystal-core fibers may be available sooner or later.

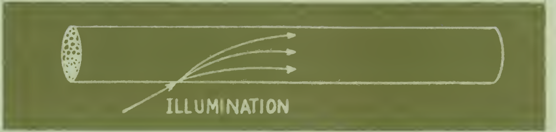
[10] Antifriction coatings of the silicone family lose their desirable properties around 800° F. Talc or graphite is more suitable for high temperatures.

[11] If fatigue from repeated bending exists, it is masked by static fatigue, i.e. a decrease of strength with time under prolonged load.

IMAGE CONDUIT

This is similar to the flexible fiberscope, but the fibers are fused together, and therefore there is little or no flexibility. The image conduit can, however, be bent with a torch to conform to any desired path.

Illuminating image conduit can be supplied, allowing a uniform light field to be injected from the side and carried in the direction opposite the image in separate channels. This serves the purposes of illuminating an object too close for other types of illumination.



Under certain conditions standard image conduit can also be illuminated from the side, using the same channels as the image, but this is apt to produce poorer contrast.

OPTICAL MOSAICS

These are fused blocks of aligned fibers which can be thick, thin, large, small, tapered, distorted, bent, etc. The term is not applied to flexible bundles with fused ends.

In calculating transmission through an optical mosaic there are several factors to account for. First of all, surface reflection off both entrance and exit surface are given by the Fresnel equations.[12] Second, the area occupied by the cladding is wasted. This area factor may run from 8 to 30 per cent.[13] Third, the numerical aperture and the incident light distribution determine the fraction of the angular distribution transmitted. Fourth, there will be some absorption or scattering, though this is usually negligible in thin pieces

[12] For normal incidence the energy reflection is $\left(\frac{N^1 - N^2}{N^1 + N^2}\right)^2$. Practically speaking, with the indices commonly used, the energy reflection averaged over the two polarizations doesn't change much out to 45°.

[13] The cladding thickness necessary to avoid cross talk depends on fiber diameter, wave length, indices of refraction, and angle of incidence. The resonance theory of cross talk is beyond the scope of this paper, but we can generalize in a negative way. It is not necessary to prevent light interaction between adjacent fibers so long as they don't resonate; it is necessary only to keep the interaction low over one beat length. For a fiber immersed in a continuous high index medium, a much heavier cladding is required.

except at the ends of the transmission spectrum. When extramural absorption is used there will be some extra absorption of image light and some decrease in the nominal numerical aperture.

One should beware of careless experimental measurements of transmission efficiency. For instance, an extramural absorption mosaic always shows less total transmission than a clear piece of the same numerical aperture for the simple reason that the background light is eliminated. The image itself may be just as intense and the contrast may be much improved.

FIBER OPTICS SCRAMBLER

Often discussed but seldom executed, this

is like a fiberscope except that the middle section of loose fiber is deliberately disoriented as much as possible, then potted and sawed. Each half is then capable of coding a picture which can then be decoded by the other half.

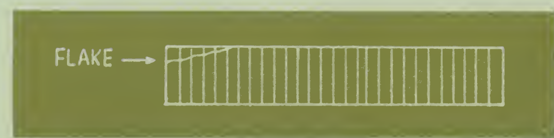
THERMAL AND MECHANICAL CONSIDERATIONS

In the discussion of singles we covered some of this ground.

SEALING OF FIBER OPTICS—Optical mosaics are often sealed to glass or metal for electronic applications. Nothing very general can be said about the proper method of use since there is a great variety of material available and no doubt more to come. Most presently made are designed to seal to G-12 glass, Sylvania No. 4 metal, or the expansion equivalent. There is a good possibility that Kovar sealing mosaics will soon be available if they aren't already.

STRENGTH—One thing is true of most mosaics, namely that they break anisotrop-

ically. Cracks tend to run cross-grain, and so there is an increased susceptibility to flak-



ing. Otherwise they behave much like any other glass. They can be ground and polished like homogeneous glass, but the customer should check carefully with the manufacturer before attempting this. For vacuum tube fiber optic windows a conservative rule of thumb is a 16-to-1 ratio of diameter to thickness.

Since optical mosaics are at least two and sometimes three glass systems, it is necessary to ask the manufacturer for annealing instructions. Some mosaics can be processed completely below the annealing temperatures of all the components. In others there are two or three annealing ranges to take care of. Excessive temperatures can cause devitrification, porosity, surface ripple, sagging, or discoloration.

CHEMICAL CONSIDERATIONS

Optical mosaics are often made of lead oxide or lanthanum oxide glass. Neither of these weathers well. The lead oxide turns black in a reducing atmosphere at elevated temperatures and poisons most photocathodes. The lanthanum oxide glasses weather very badly and can't be subjected to normal cleaning processes. However, they don't poison most photocathodes. Many other types are available so that it is impossible to generalize. Most glasses brown appreciably in a high radiation field.

PROTECTIVE COATINGS

Manufacturers supply optical mosaics with protective surface coatings of one kind or another. Antireflection coatings and transparent conductive coatings can also be applied to some types. The temperature for applying Nesa coatings will damage some mosaics. In

this case, a thin gold bismuth evaporated coating is preferable.[14]

HOW IS FIBER OPTICS USED?

Flexible Fibers—as bundles of optical fibers or light guides in applications like data processing, fire detection, scanning, counting and sizing. Light guides are useful where "cold light" is required such as in operating rooms and explosive atmospheres.

Flexible Image Guides—medical endoscopes, industrial borescopes and other situations that require transmission of an image over complicated optical paths.

Rigid Image Conduit—Same as flexible image guides where no permanent flexibility is required. Rotary joints can give some flexibility.

Mosaic Sheet—single line handling, as in converting a line to a circle for facsimile and reconnaissance systems. Line scan borescopes for nuclear fuel element inspection.

Fused Tapers—Enlarging cathode ray tube outputs, magnifying instrument dials, microfilm reading, and data display.

Projection Screens—As a replacement for ground glass screens where light conservation is essential, and viewing of the screen will be in high ambient lighting conditions (cockpit information displays). These screens, which are very thin non-vacuum tight fiber face-

[14] It is also possible to obtain intagliated cladding with a metallic web in the mote.

plates, also have excellent off-axis viewing characteristics.

Field Flatteners—Fiber optic field flatteners are used to match the field curvature of optical to electron-optical systems, and to match the field curvatures of two parts of an optical system. Field flatteners with angular correction are also available.

Fiber Optic Faceplates—are now being used in special image orthicons, vidicons, cathode ray tubes, storage tubes and image intensifiers. In all of these applications the basic function of the fiber optics is to transport an image into or out of the vacuum enclosure. As an image transport they are nearly equivalent to a zero thickness window.

The potential uses for fiber optics devices are almost limitless, current areas of interest include high-speed data handling and retrieval, and simultaneous imaging and switching for computer applications.

Many remote indicators or sensors can be envisioned that would conduct not only light, but alpha-numeric characters for reading or recording. Flying spot scanners can be fabricated that will eliminate costly, dangerous high-vacuum tubes and associated electronics. More exotic uses would be in conjunction with laser-recorders and semiconductor light energy sources. For the medically oriented, fiber optics has already provided a means of observing normally inaccessible portions of the human body. Fibers can also provide a source of high-intensity cold light for medical photography, or photography in explosive atmospheres.

The military can use it for periscopes, fluid level indicators and remote viewers for hazardous operations. High speed X-ray photography and motion picture printing are also

among the users of fiber optics. The list of possible applications is endless, and limited only by the imagination and inventiveness of the Engineer or Scientist.

GLOSSARY

APERTURE PLATE—A plate with ema and limited n.a. introduced in a system only to decrease or control n.a.

CHICKEN WIRE—*See* Mosaic Construction.

CROSS TALK—The observable leakage of light from one fiber to another. This is not usually taken to include the light outside the n.a. which migrates. Sometimes it is used to include light which goes over by scattering defects but usually refers only to simple electromagnetic tunneling. A clear, high index buffering web can eliminate first order interaction, in some cases, at the expense of general background leakage, and an opaque high index web can do the same at the expense of transmission.

DISPERSION—A measure of change in index of refraction with wavelength for a material. In lens optics this leads to chromatic aberrations. In fiber optics only n.a. and field angle are affected by dispersion.

EFFECTIVE N.A.—Always less than nominal n.a. since either the resolving power or transmission must drop drastically near the nominal n.a. One must specify carefully a desired operational result in order to define an effective n.a.

EXTRAMURAL ABSORPTION or EMA—Opaque second cladding used to eliminate unconducted light.

f/NUMBER—$\dfrac{1}{2 \text{ n.a.}}$

HARD PACK—A construction in which the fibers retain an approximately circular cross section and the cladding fills the voids. So called because it occurs when the core glass is more viscous than the cladding while fusing.

INTAGLIATION—Surface sculpting used for control of field angle, insetting of surface coatings, etc.

MEAN TRANSMISSION LENGTH or MEAN LENGTH—Transmission of light of wave length at angle varies as

$$I = I_0\, e - \frac{l}{L\,(\theta_1{}^2)}$$

when L is the mean length. Since L is a function of θ, the integrated transmission doesn't fall off as a simple exponential.

As a rule $L\,(\theta)$ decreases monotonically with θ.

If surface losses predominate, then

$$L\,(\theta) \approx \mathrm{Cot.}\,\theta.[15]$$

If body losses predominate, $L\,(\theta) \approx \mathrm{Cos}\,\theta$.

MOSAIC CONSTRUCTION—A construction in which fibers are grouped and regrouped to build up an area. This usually results in some degree or type of imperfection at the boundaries of the subgroup. When this boundary condition becomes very noticeable it is called *chicken wire.*

[15] This is one of the three classical fallacies of fiber optics, and is repeated here for simplicity and out of respect for tradition. Losses due to many kinds of surface defects are either to a first approximation independent of angle, or dependent on some function other than cot θ.

NOMINAL N.A. = $\sqrt{n_1{}^2 - n_2{}^2}$.

NUMERICAL APERTURE or N.A.—Sine of the acceptance half angle, sine of the filled half angle.

PACKING FRACTION or PF—Fractional area occupied by core material in an optical mosaic.

RESOLVING POWER—Usually measured in optical line pairs per unit length. It is the maximum number of high contrast square edge black and white lines that can be counted with certainty. To some extent this is subjective and is never a complete description of resolution capability. Sometimes stated as TV lines in which units the resolving power is twice as great. Except in optical mosaics that are very heavily clad, the resolving power falls off as approaches the nominal n.a.

SOFT PACK—A construction in which the cores deform to fill the space leaving a cladding wall of more or less uniform thickness—as in a honeycomb.

UNIT CONSTRUCTION — One in which there are no subgroups.